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Electronic Temperature Estimation in Induction Heating Processes

Prof. D. Schulze, Dipl.-Ing. T. Zehringer

1 Introduction

The industrial implementation of induction heating processes often prohibits temperature measurement of the heated work, hence the idea to investigate the behaviour of inductor voltage and current with respect to the work temperature. For the magnetic-coupling is temperature-dependent, the electric and magnetic quantities too are changing with the inductor temperature and especially the work temperature. This research attempts to answer the following questions: Firstly, is it possible to to estimate the work temperature of an induction heating process via measuring an electrical quantity? Secondly, how accurate is this temperature estimation?

Figure 1 illustrates the closed loop of the induction equipment. The power line is connected to the power input of the frequency converter. The converter outputs the generated voltage. The related power is converted into heat by the induction equipment. The new output is the temperature, which has feedbacks to the frequency converter and the inductor. By applying the measurement device an information output is added. Its output is the quantity X. Now the system of frequency converter and inductor is simply considered as one black box, which lefts just the temperature as input and the quantity X as output.

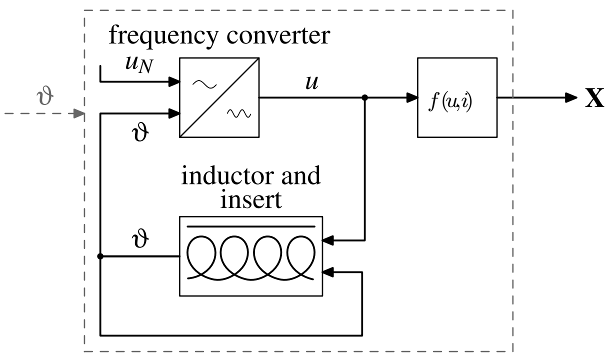


Figure 1: Closed loop

2 Measurement

The main task of the research is the measurement of the inductor voltage and current and of the work temperature. For those quantities have fluctuations, e.g. caused by the power line, rational quantities were chosen for compensation. The quantity X may be one of the following:

$\hat{Z}$	is the quotient of the maximal voltage amplitude and maximal current amplitude. It is calculated as the mean value of the amplitudes of each measurement timeframe.
Z	refers to the quotient of the RMS-values of voltage and current.
λ	The power factor is defined as the quotient of real power and apparent power.
f	The frequency is the only quantity not defined as a ratio, but for the frequency is generated, there should not be much influence caused by the power line.
$k_{U/I}$	The distortion factor is defined as the quotient of RMS value of all harmonics and the RMS value of the whole signal.
THD	The total harmonic distortion factor describes the ratio of the RMS value of all harmonics and the RMS value of the basic oscillation.
$\frac{u_3}{u_1}$	represents the ratio of the RMS value of the third harmonic and the RMS value of the basic oscillation.
$\cos(\varphi_1)$	is defined as the power factor of the basic oscillation.

Table 1: Chosen quantities for temperature estimation

For the set-up the following equipment was used.

- temperature limiter
- frequency converter
- pancake inductor
- metall sheet work-piece from iron and stainless steel
- digital storage oscilloscope
- thermal elements
- Most of the calculation was done with the open source program *Octave*, [1, 2].

Figure 2 illustrates the experimental setup. The power supply is connected to the temperature limiter, which transmits the power to the input of the frequency converter followed by the inductor. Between the converter and the inductor, the shunt for current measurement is attached. The voltage is measured on the inductor contacts. Both measurement signals are connected to the digital storage oscilloscope.

The thermal element is attached to the centre of the work. The equaliser is connected in parallel to the digital storage oscilloscope and the temperature limiter.

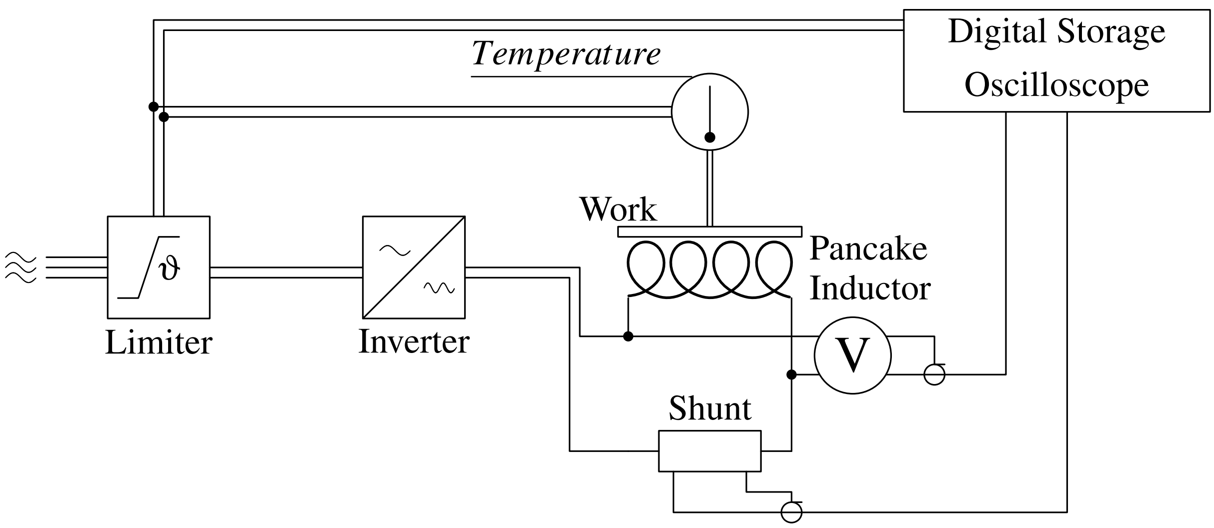


Figure 2: Experimental setup

Due to the large amount of data at a sampling rate of 10 MHz, a sequential measurement is required. Figure 3 shows one sequence of the measurement. One sequence is henceforth refered to as timeframe.

The peak value of both signals, voltage and current, follows some envelope. The duration of the envelope is $t_E = 10$ ms. For a timeframe shorter, the trigger has to be accurately defined. In other words: A single trigger condition, e.g. a trigger level is not sufficient.

Hence, if the first trigger condition is satisfied, a second condition must become true after a predefined delay time to finaly trigger the measurement. The delay time t_d must ensure that the measurement is triggered exactly when the signal enters the time span t_{TL}, where the signal's apmlitude is above the trigger level. The time span t_{TL} is followed by the fall time t_f and the rise time t_r. This leads to the following condition for t_d:

$$t_{TL} < t_d < t_f + t_r \tag{1}$$

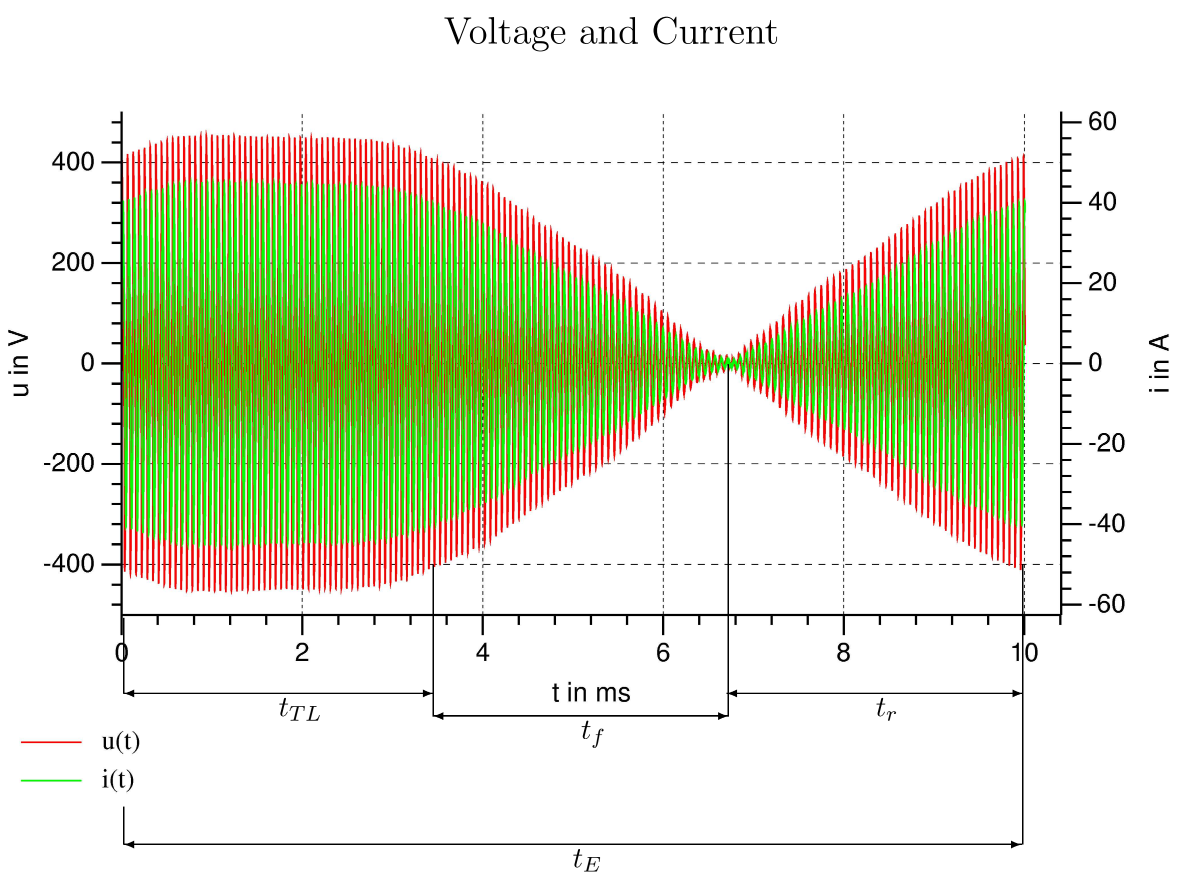


Figure 3: Voltage and current of one sequence

3 Data Processing

3.1 Curve Fitting

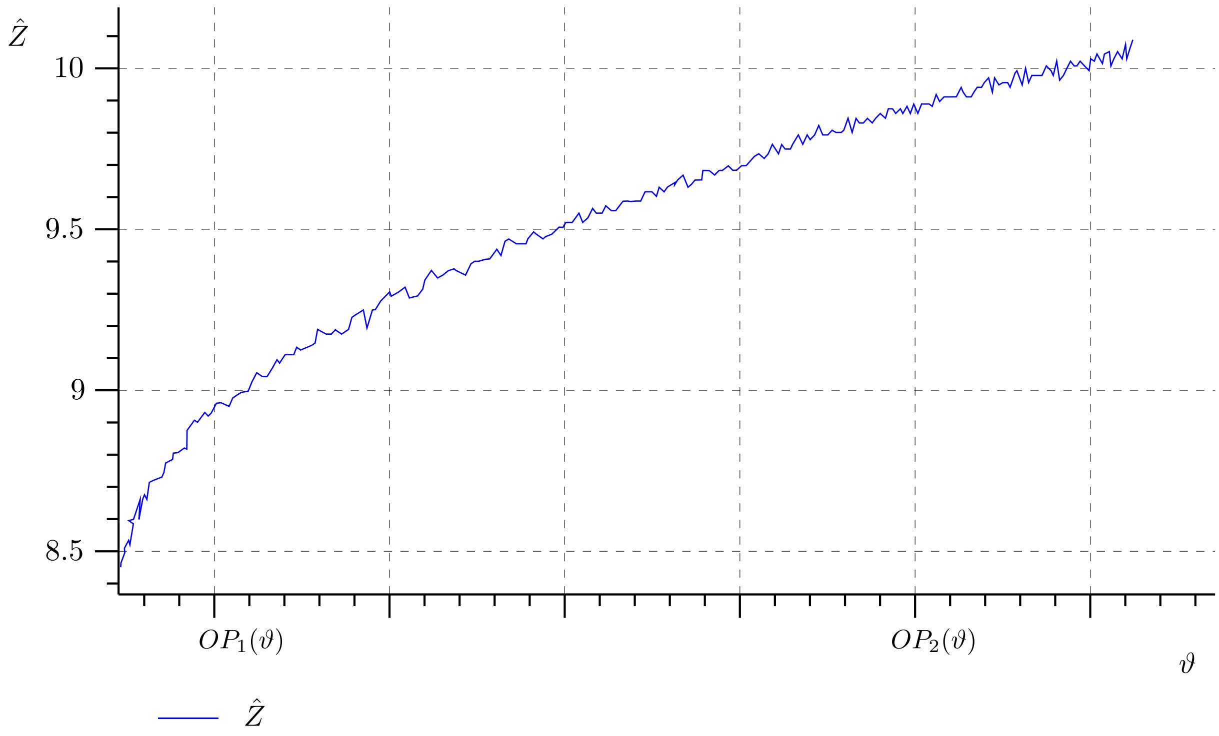


Figure 4: Measured curve from peak values of voltage and current, $\hat{Z}$ - iron work

In figure 4, the peak ratio $\hat{Z}$ is illustrated against the temperature, showing some saturation. The operating points OP_1 and OP_2 indicate the temperature range of interest. A mathematical description for the curve is achieved by curve fitting [3]:

First, there are some considerations about the mathematical function which has to be obtained. After a closer look on figure 4, a linear term combined to a saturation function will satisfy. In the now following general approach X stands for any possible quantity, e.g. for $\hat{Z}$ in figure 4.

$$\vartheta(X) = aX + c \tag{2}$$

$$\vartheta(X) = bX\mathbf{e}^{\alpha X} \tag{3}$$

$$\vartheta(X) = aX + bX\mathbf{e}^{\alpha X} + c \tag{4}$$

By use of such a function, it is possible to calculate several linear and non-linear curves. If the curve shows an extreme value, the function must be split into 2 sub-functions.

$$\vartheta(X) = \begin{cases} a_1 X + b_1 X \mathbf{e}^{\alpha_1 X} + c_1 \\ a_2 X + b_2 X \mathbf{e}^{\alpha_2 X} + c_2 \end{cases} \tag{5}$$

The parameters a, b, c and α are obtained by the Levenberg – Marquardt – Method [4]. An adequate algorithm is already implemented in the open-source computing program *octave*.

The red line in figure 5 shows the result of the curve fitting.

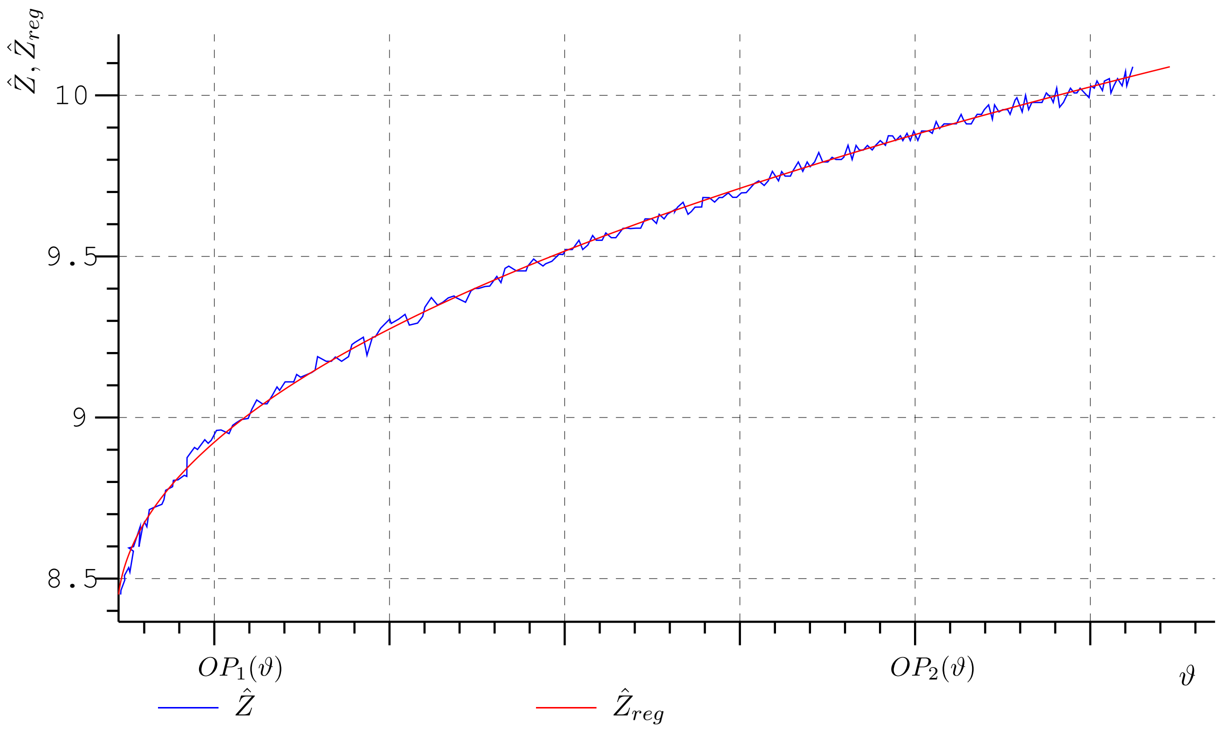


Figure 5: Fitted curve of peak values of voltage and current, $\hat{Z}$ - iron work

The new task is to estimate how accurately the temperature is to be calculated via the obtained parameters. Therefore, the calculated temperature $\vartheta(x)$ is subtracted from the measured ϑ_m, regarding positive and negative difference separately.

$$\Delta\vartheta = \vartheta_m - \vartheta(X) \tag{6}$$

$$\Delta\vartheta_+ = \begin{cases} \Delta\vartheta & \forall \quad \Delta\vartheta > 0 \\ 0 & else \end{cases} \tag{7}$$

$$\Delta\vartheta_- = \begin{cases} \Delta\vartheta & \forall \quad \Delta\vartheta < 0 \\ 0 & else \end{cases} \tag{8}$$

The differences are now fitted by 4^{th} order regression. Afterwards the regression curve is filtered recursively by a penalty function until each value is beyond the values of differences ($\Delta\vartheta_+ \rightarrow \Delta\vartheta_{reg+}$, $\Delta\vartheta_- \rightarrow \Delta\vartheta_{reg-}$). Afterwards those filtered values $\Delta\vartheta_{reg\pm}$ are added to the temperature curve obtained by curve fitting: The result are the positive and negative temperature tolerance.

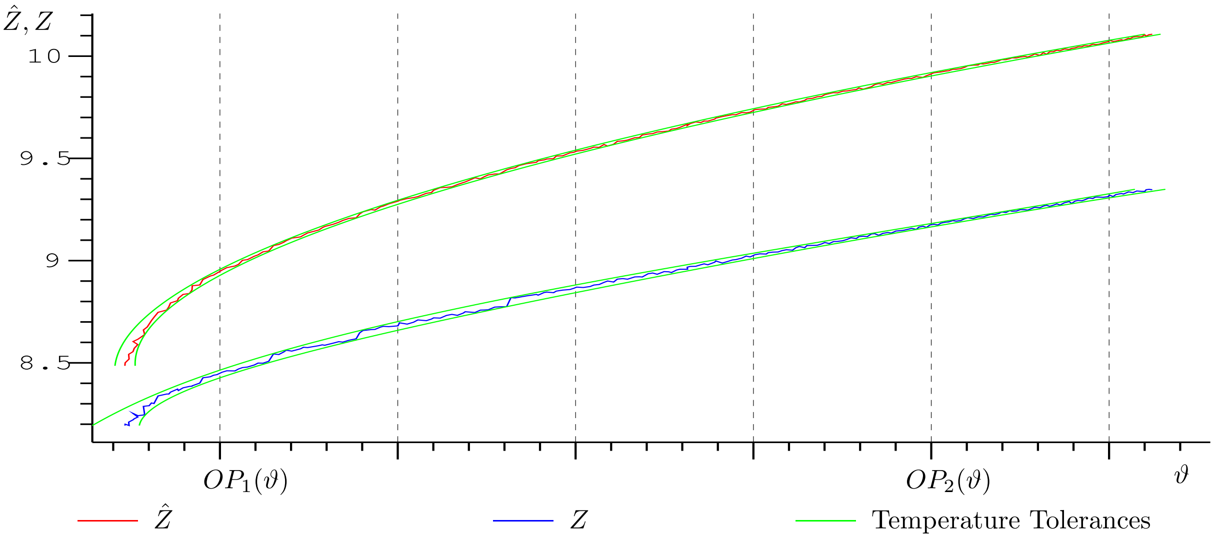
$$\vartheta_{1/2} = \vartheta(X) + \Delta\vartheta_{reg\pm} \tag{9}$$

The temperature tolerances are forming an envelope along the measured signal and the fitted curve, as shown in figure 6(a). Hence the quality is finally calculated as

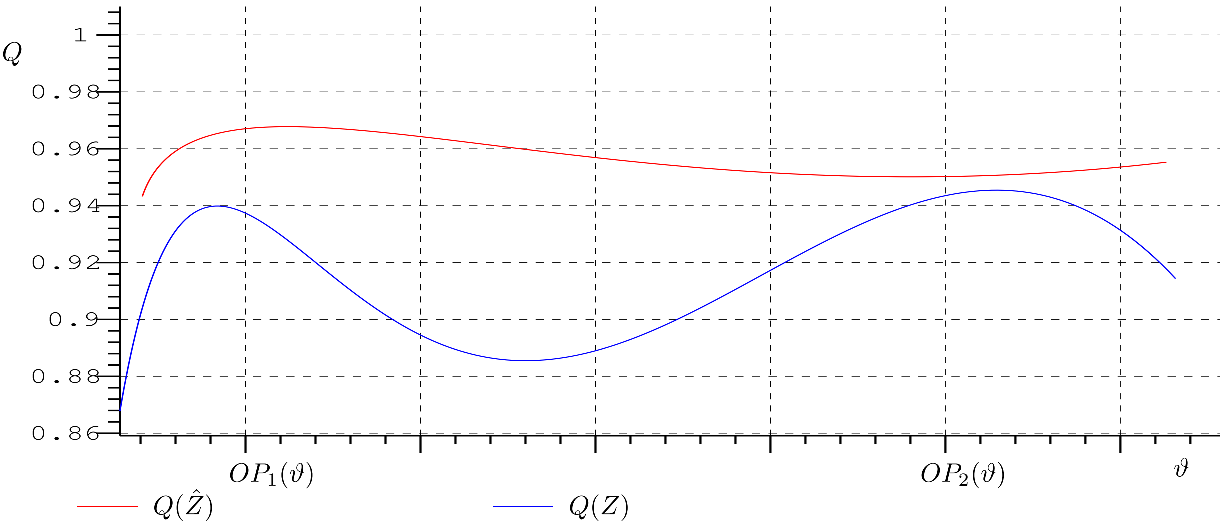
$$Q = 1 - \frac{|\vartheta_1 - \vartheta 2|}{100 \text{ K}}. \tag{10}$$

The denominator of 100 K was chosen firstly, for there is no need for a relative but for absolute quality, and secondly, for it is simple to calculate the numerical value of the temperature tolerance via the quality. A quality of 0,75 leads to a tolerance of 25 K.

The calculated quality is shown in figure 6(b). Surprisingly the quality is worse at high temperatures than at the beginning temperature despite having less noise on the measurement signal. This is due to the lesser gradient of the curve at higher temperatures. The lesser the gradient the less accurate the temperature estimation.



(a) Temperature tolerances envelopes along the measured signal $\hat{Z}, Z$



(b) Quality of temperature estimation $\hat{Z}$ and Z

Figure 6: Temperature estimation by magnitude and RMS ratio for iron work

3.2 Fourier Transformation

The calculation of the second half of the quantities announced in table 1 requires the Fast Fourier Transformation. The Fourier series is defined as a sum of sinus and cosinus functions, [5].

$$u(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \Big(a_n \cdot \cos(n\omega t) + b_n \cdot \sin(n\omega t) \Big) \tag{11}$$

The complex Fourier series is the base of the Fast Fourier Transformation (FFT) which is used for time-discrete quantities.

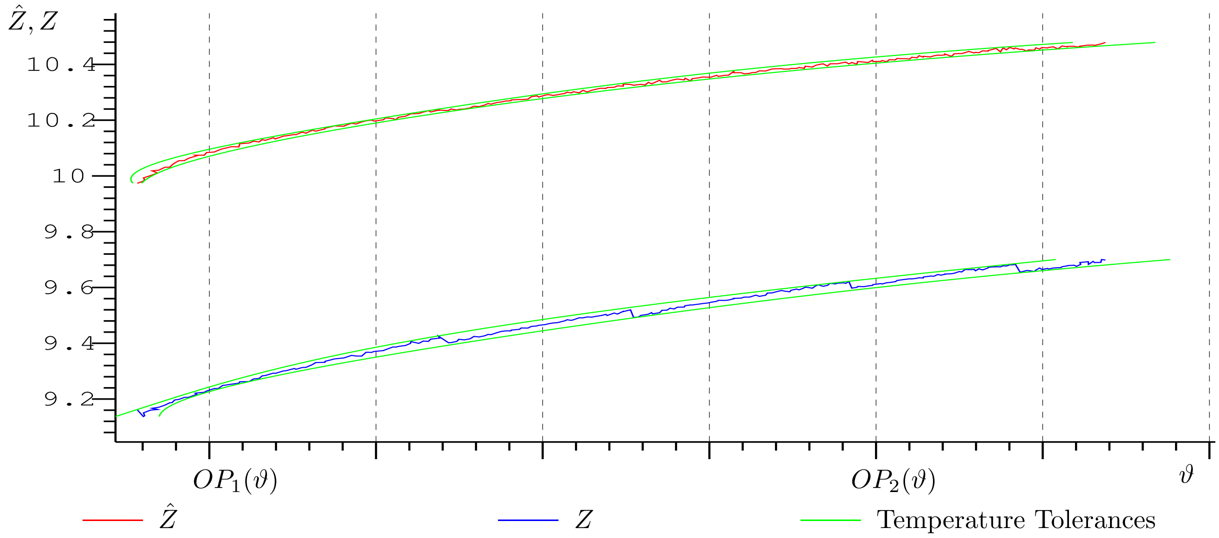
$$u(t) = \sum_{n=-\infty}^{\infty} C_n e^{jn\omega t} \tag{12}$$

There are some unfavourable signal attributes. Firstly, it is a time-discrete signal. Secondly, neither the frequency nor the amplitudes are constant. But then there is one advantage too. With respect to the task announced in the introduction, the signal may be considered as noiseless. Hence the frequency for each timeframe may be obtained as the mean value from all periods. Therefore zero-crossings of each period are determined via straight line approximation of the measured values, and the cycle duration is calculated. For approximately constant amplitudes only those values higher than the trigger level are considered. Finally, the mean value of the FFT for one timeframe from each period is calculated.

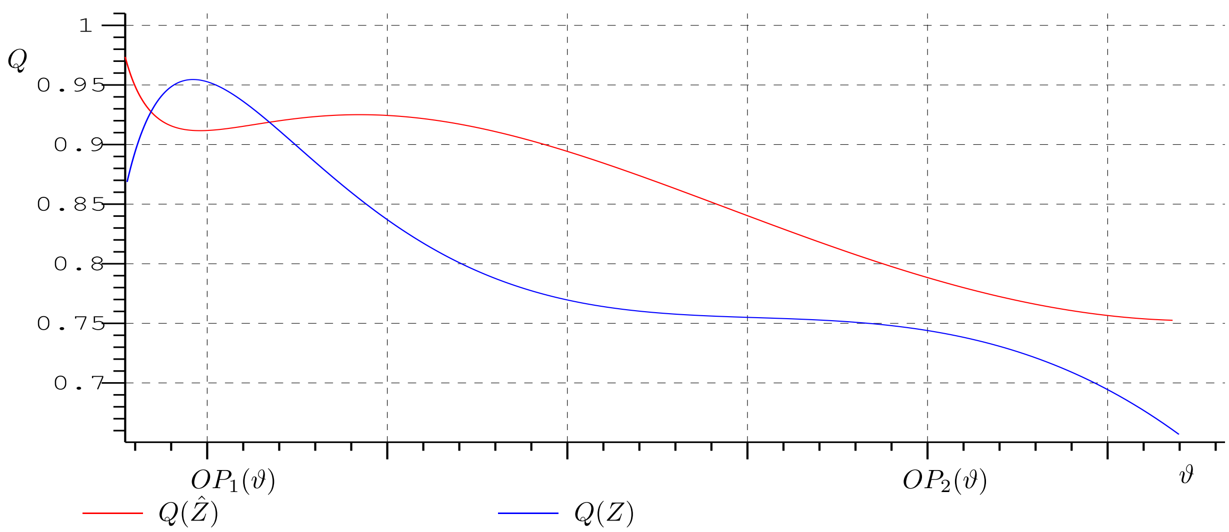
4 Results

The results for the magnitude ratio and the RMS ratio for the iron work were already shown by declaring the curve fitting and qualification. Figure 7(a) shows the temperature dependency of the magnitude and RMS ratio for the stainless steel work. The quality of the temperature estimation using this quantity is shown in figure 7(b).

The curves of both work types show quite good results in temperature estimation, where the ones for the iron work are more accurate than those for stainless steel.



(a) Temperature tolerances envelope along $\hat{Z}$ and Z



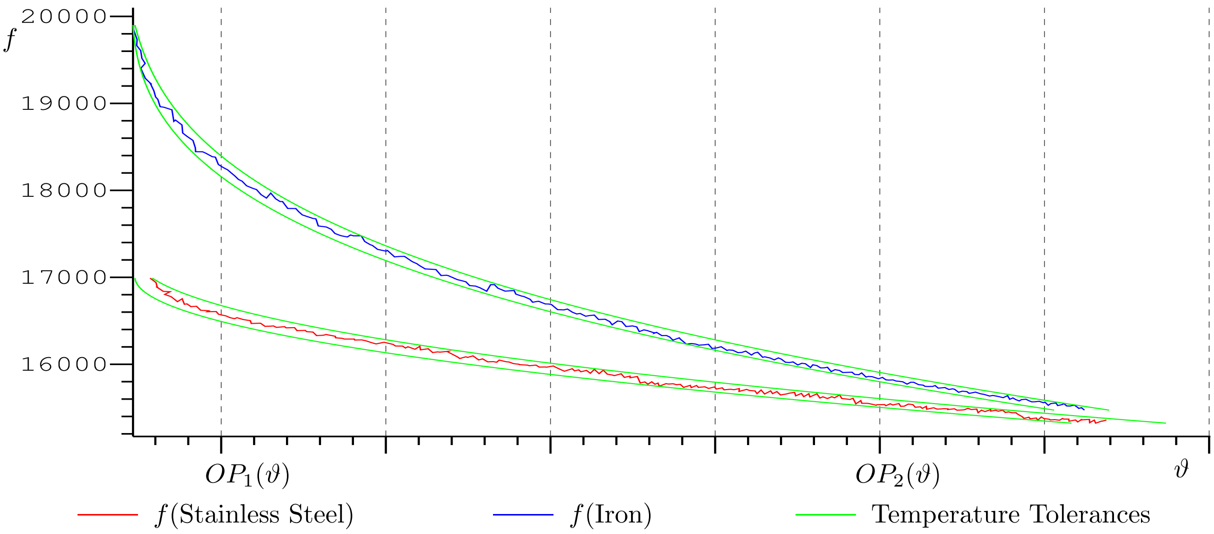
(b) Quality of temperature estimation $\hat{Z}$ and Z

Figure 7: Temperature estimation by magnitude and RMS ratio for stainless steel

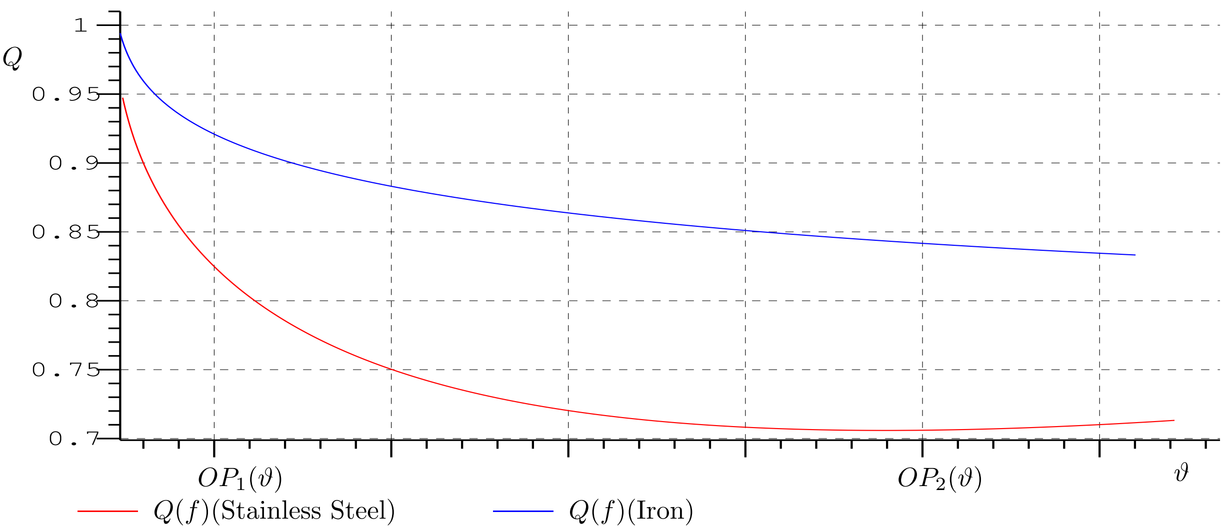
4.1 Frequency

In the previous section, the frequency was found not to be constant. Thus the frequency was determined in analogy to the FFT by calculating the mean value for one sequence from each period.

The temperature dependency of the frequency is shown in figure 8(a). There are two curves, one for an iron work and the other for stainless steel. For the gradient of the stainless steel curve is lesser than the one of the iron curve, the frequency results in lower quality for stainless steel, figure 8(b).



(a) Temperature tolerances envelope along the measured frequency



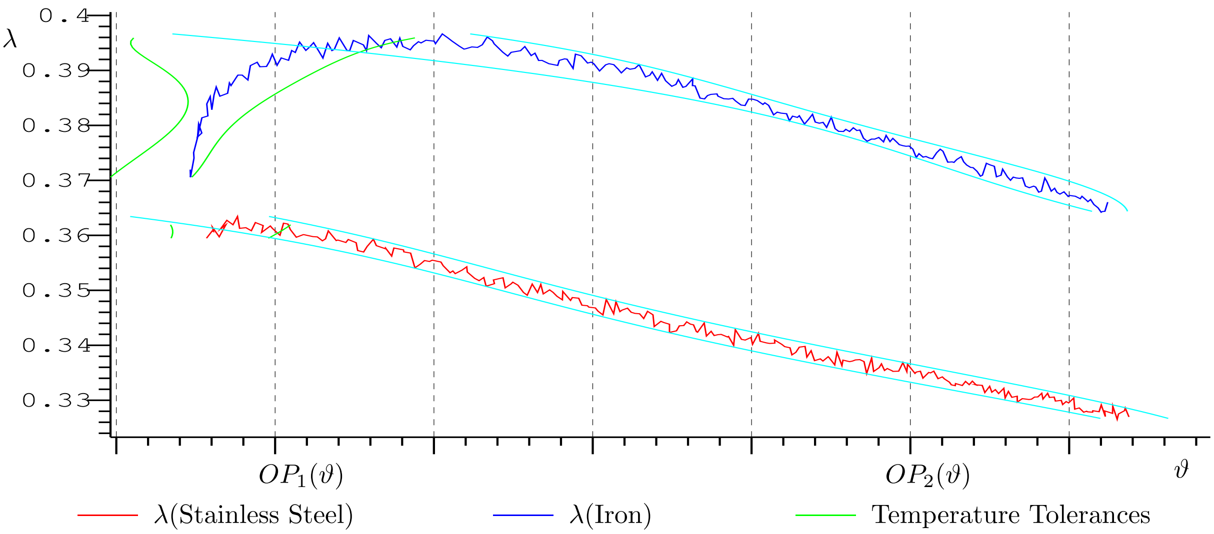
(b) Quality of temperature estimation via frequency

Figure 8: Temperature estimation via frequency

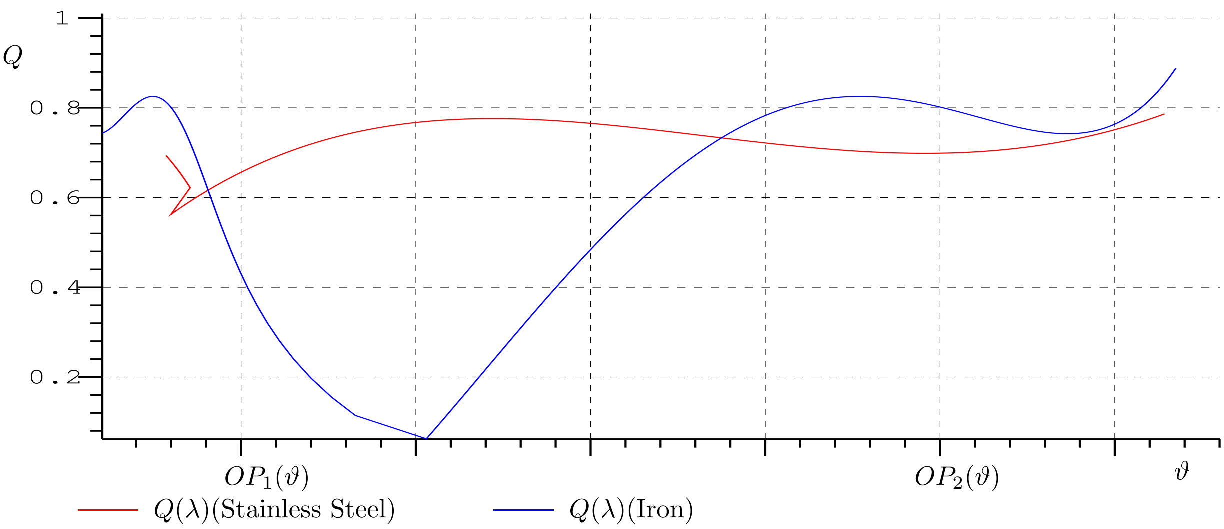
4.2 Powerfactor, λ

Figure 9(a) illustrates the powerfactor against the temperature. The curve for the iron work shows some maximum. For the gradient in the maximum tends to zero, the quality of the temperature estimation, figure 9(b), is bad, despite the curve fitting function being split into 2 sub-functions according equation (5).

The stainless steel curve comes with almost negative, linear slope and hence still leads to satisfactory results.



(a) Power factor dependency of temperature

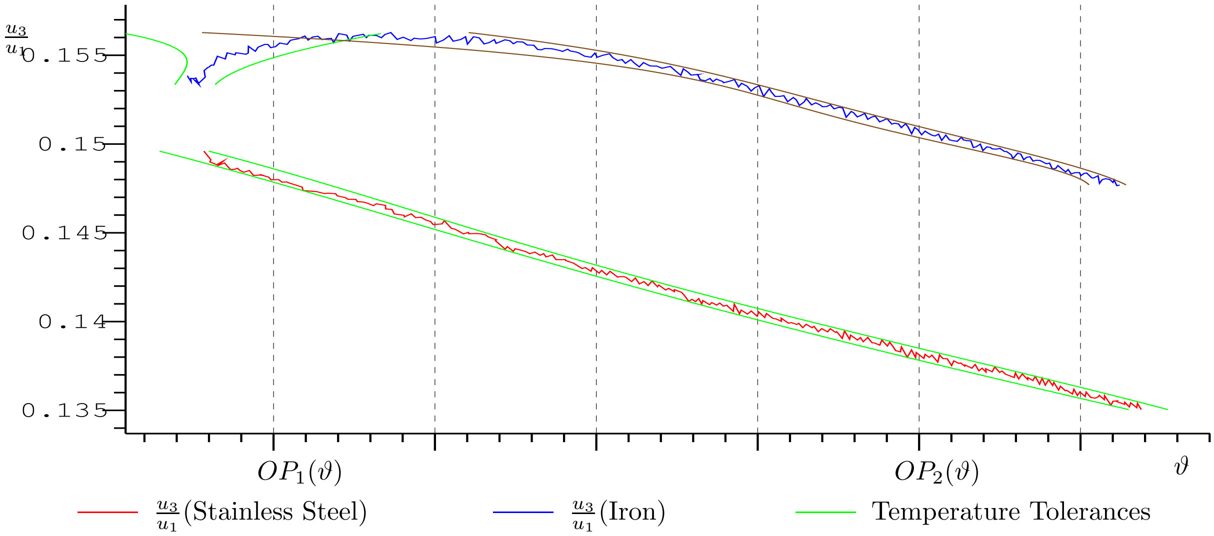


(b) Quality of temperature estimation via power factor

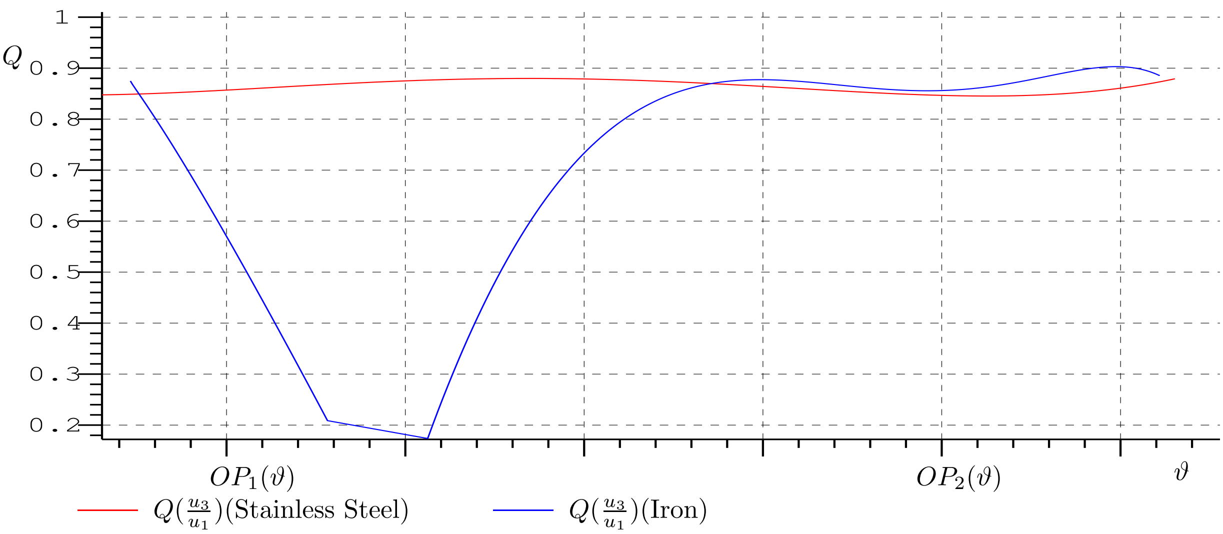
Figure 9: Temperature estimation via powerfactor

4.3 Ratio of third voltage harmonic and base frequency, $\frac{u_3}{u_1}$

Figure 10(a) shows the ratio of the third voltage harmonic and base frequency against the temperature. For the iron work, there is the same problem of a maximum as announced before. The stainless steel curve shows negative, linear slope again, but leading to quite accurate results this time, figure 10(b).



(a) $\frac{u_3}{u_1}$ dependency of temperature

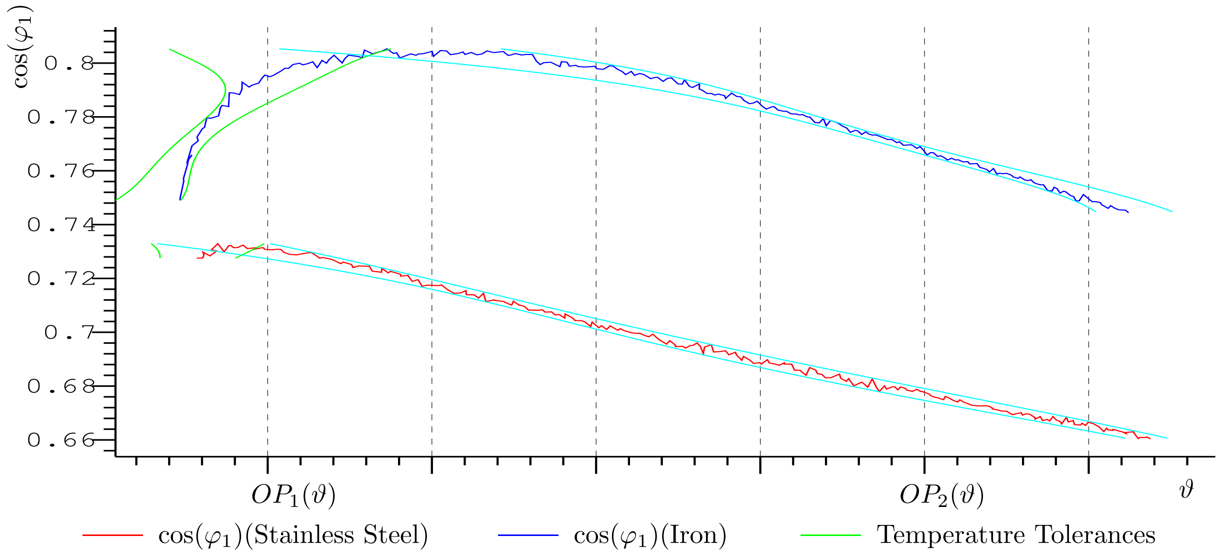


(b) Quality of temperature estimation via $\frac{u_3}{u_1}$

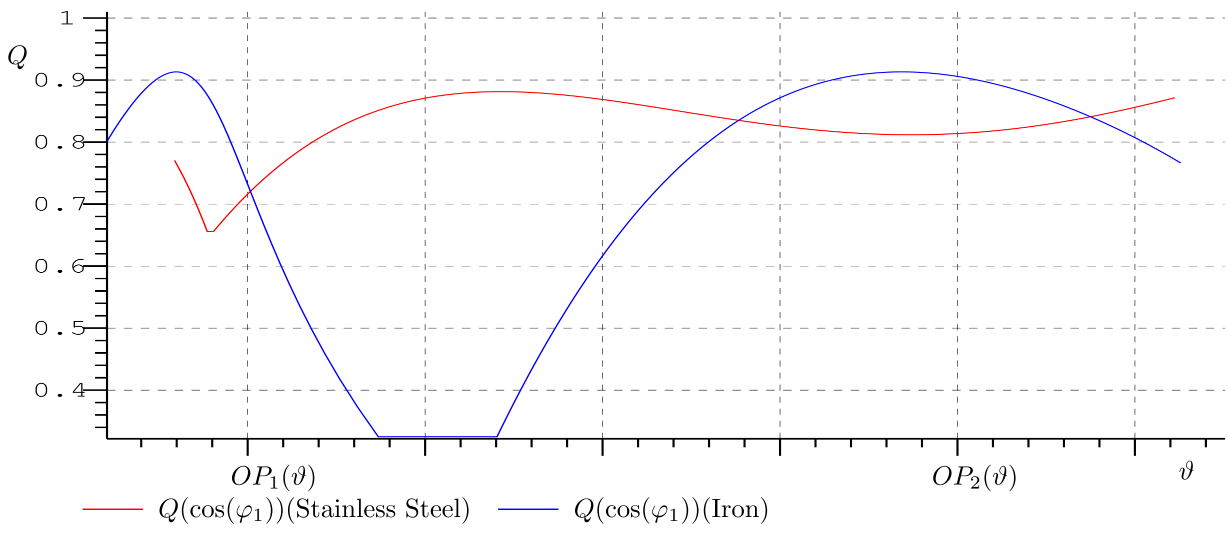
Figure 10: Temperature estimation via $\frac{u_3}{u_1}$

4.4 Power factor of the base frequency, $\cos(\varphi_1)$

The powerfactor of the base frequency is shown against the temperature in figure 11(a). The curve progressions are similar to those for the powerfactor before. Again the stainless steel work leads to better results than the iron work, figure 11(b).



(a) $\cos(\varphi_1)$ dependency of temperature



(b) Quality of temperature estimation via $\cos(\varphi_1)$

Figure 11: Temperature estimation via $\cos(\varphi_1)$

5 Conclusion

Generally, temperature estimation via electrical quantities leads to satisfying results. The temperature estimation has proven more accurate for iron than for stainless steel.

In the last section, six of the eight quantities announced in table 1 to be investigated have been presented. After some repetitions of the experiment, there are finally four quantities with satisfying results:

$$\hat{Z}, Z, f, cos(\varphi)$$

These quantities allow an estimation with a quality of $Q > 0.7$, which means an uncertainty of 30 °C.

5.1 Requirements

5.2 Set-up restrictions

For accurate results in temperature estimation, there are some restrictions concerning the setup. It is essential, that the setup does not change once the curve fitting function has been determined.

- The coupling gap between the inductor and the workpiece must not change.
- The frequency converter must not change.
- The work position must always be the same.

5.3 Hardware

All measurements were done at a sample rate of 10 MHz. If the sample rate is altered, the results will differ, too, especially, when switching to lower sample rates. There is a dependency of sample rate f_S, measurement duration t_M and memory usage C_M. For example $t_M = 2$ ms, $f_S = 10$ MHz:

$$C_M = f_S \cdot t_M$$
$$C_M = 10^7 \cdot 2 \cdot 10^{-3} \cdot 10^{-3} \text{ kW} = 20 \text{ kW} \qquad \text{kW} \rightarrow \text{kilo words}$$

6 Prospects

There was just the work temperature measured. On further experiment the measurement of the inductor temperature will be included. Hence, the temperature dependent resistance might be determined, and thus the measured voltage could be corrected by the inductor loss.

Until now, the experiments are based on rising temperatures. Due to the use of thermal elements, there is some delay in the temperature measurement. Hence, the results might be more accurate if done in steady-state.

Another problem are the influences caused by electronic devices of the frequency converter. For eliminating these influences a load-controlled converter, generating a constant frequency, shall be used.

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